REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
Jan 2014

2. REPORT TYPE
Briefing Charts

3. DATES COVERED *(From - To)*
Jan 2014- Mar 2014

4. TITLE AND SUBTITLE
Rocket-Engine Injector Development: A Case Study of a Single Injector

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Malissa Lightfoot, S. Alex Schumaker, Stephen Danczyk

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q0X3

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQRC
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2014-049

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
Briefing Charts presented at University of California-Irvine Mechanical Engineering Lecture Series, University of California-Irvine, March 14, 2014. PA#14121

14. ABSTRACT
Briefing Charts

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Malissa Lightfoot
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NO *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	SAR	27	661-275-5164

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Rocket-Engine Injector Development—A Case Study of a Single Injector

Malissa D.A. Lightfoot

S. Alexander Schumaker

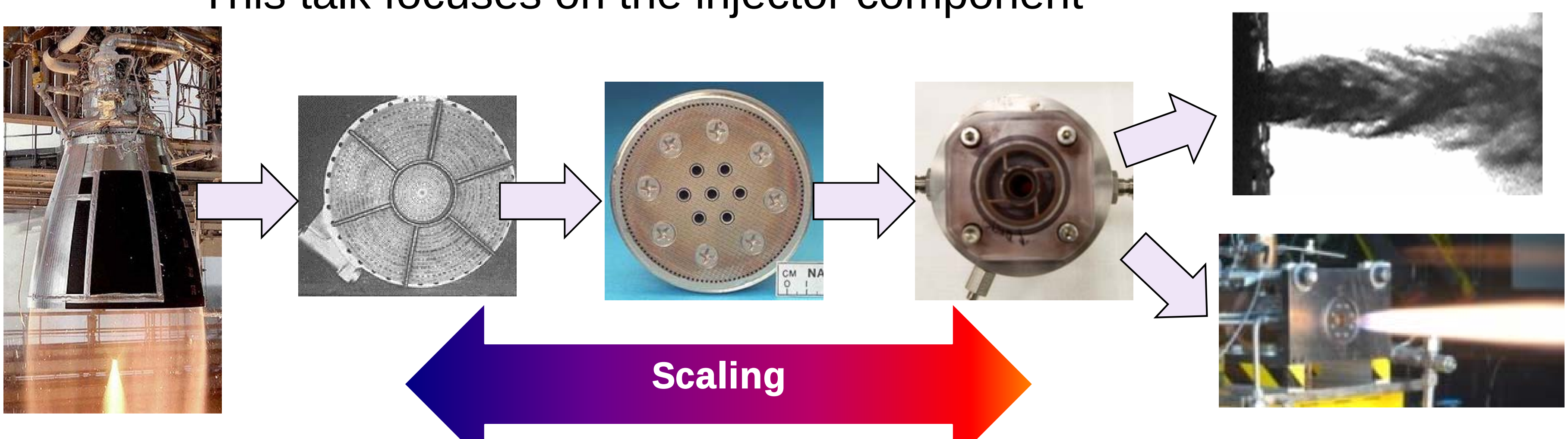
Stephen A. Danczyk

Industry Drivers

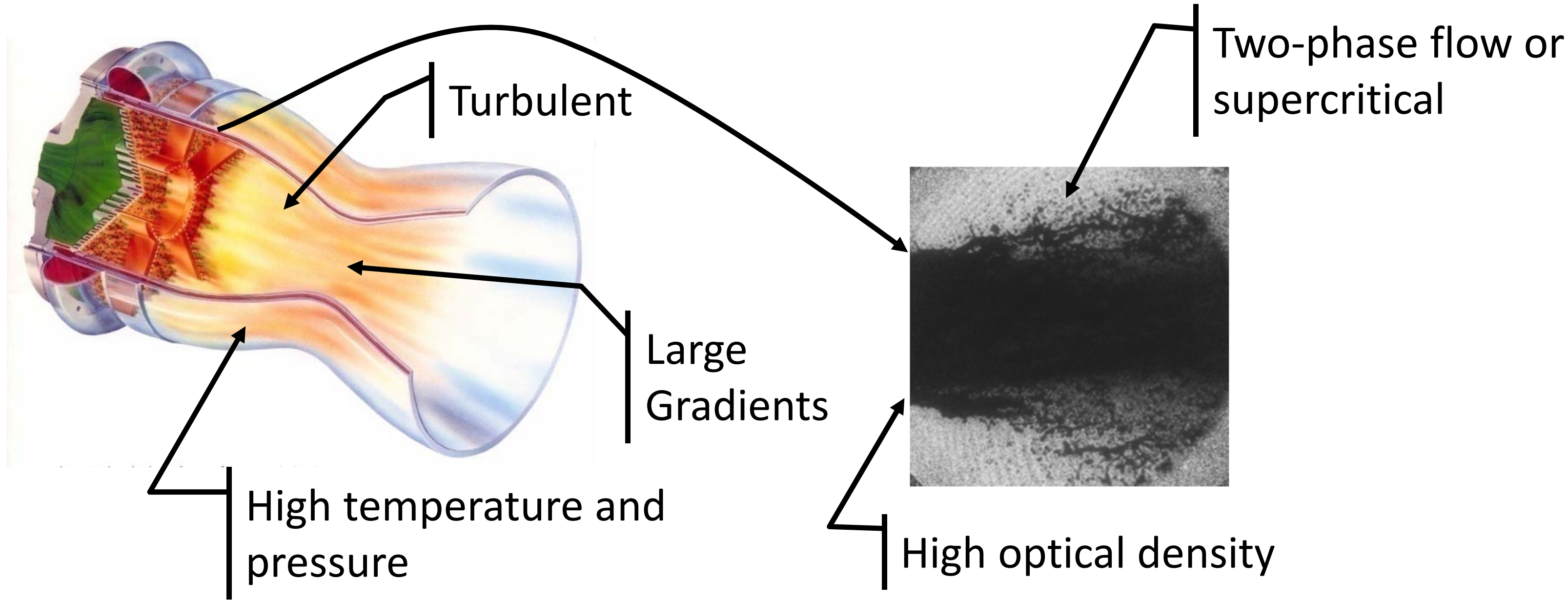
- **There is arguably more liquid rocket engine development going on in the US today than at any other time in the last 30+ years**
  - More “commercial” companies are entering the market
  - NASA’s mandates to move beyond earth orbit and retirement of the shuttle
  - AF on-going needs (move away from Russian-built engines, replace aging satellites, etc.)
- **Cost has become a main driver in these markets, but increasing performance parameters is still important to enable new missions**
- **Past rocket development been largely empirical using full-scale tests and a build-bust-redesign approach**
- **This approach is very costly and encourages incremental progress which can be inhibiting to revolutionary discoveries**

Cost Reduction

- **To reduce costs we need to rely more on modeling and on low-cost (“subscale”) testing before full-scale tests**
- **Models and low-cost testing approaches need to be demonstrated to be predictive prior to use**
- **AFRL has several programs to study individual subcomponents of the engine**
  - This talk focuses on the injector component

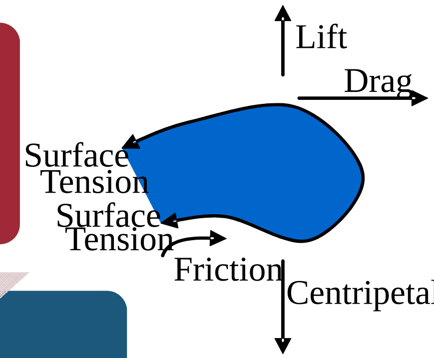


Boost-Class Rocket Engine Injectors



- **Items of importance in terms of the injector component**
  - Atomization and mixing of the propellants—determines engine performance (efficiency)
  - Sets the environment for the wall (heat transfer)
  - Key for enabling pressure balance and combustion stability

Developing Design Methods

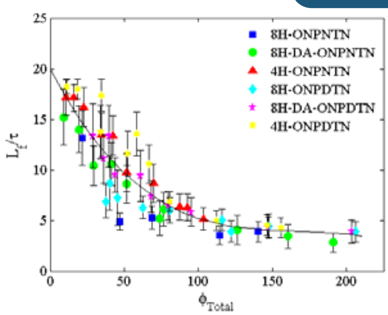


Generalized Analytical Model

- Model for gas-phase-dominated atomization is a balance of forces on a disturbance

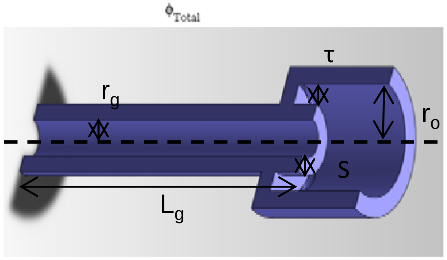
Scaling Laws

- Momentum flux ratio collapses data
- Aerodynamic forces dominate, surface tension not important



Design Criteria

- Process established for single injector type
- Encompasses geometric design details and recommended testing for verification and refinement



Injector Design and Hot-Fire

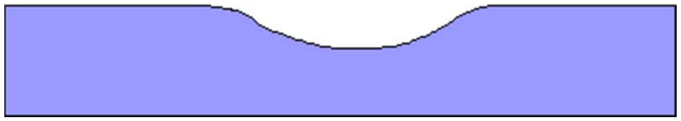
- Design injector and verify performance predictions and scaling in a combusting environment

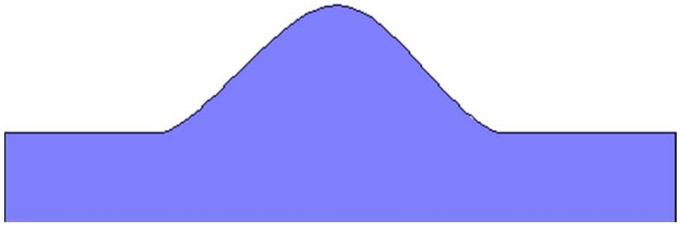
Empirical Models

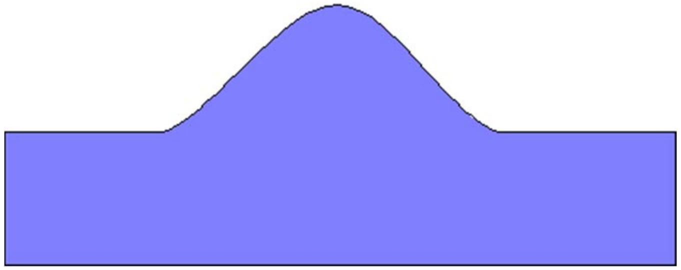
- **Empirical models exist for numerous types of injectors and have been developed for some rocket injectors over the years**
- **US experience is largely with hydrogen-oxygen engines, so correlations for injectors are typically developed for the conditions that apply there**
- **Move in the AF to liquid hydrocarbon engines, with very different mixture ratios and flow rates than hydrogen-oxygen engines**
  - Applying correlations outside of their applicability can lead to very large errors
- **Additionally, reliance on empirical correlations defines a design and operating box prematurely—preselects against revolutionary design**

A Simplified Viewpoint

- **To build a generalized atomization model, start by simplifying the problem down to the creation of a single droplet**
- **There are several ways that this may occur depending on the forces involved**
  - These are examples for situations where the gas-phase strongly participates in the droplet-making process
- **Two important processes—disturbance creation and growth / deformation to create droplet**

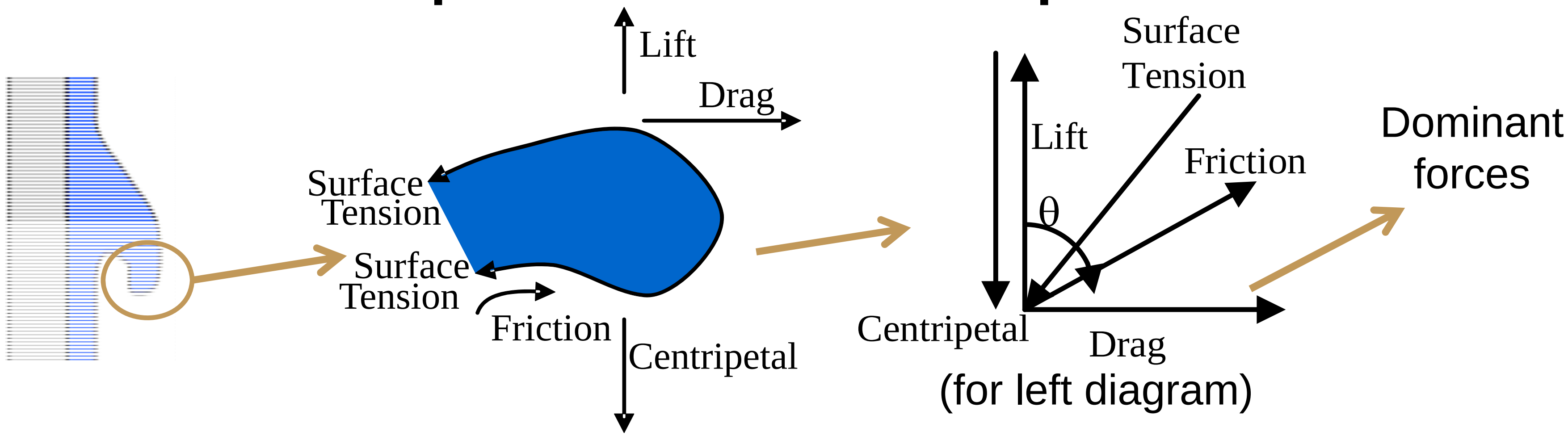






Generalized Atomization Model

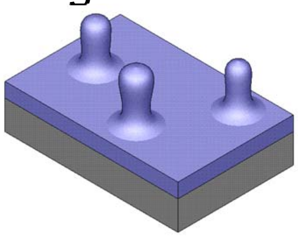
- **Based on a balance of forces acting on a disturbance of the liquid-gas interface**
- **Forces cause distortion of the disturbance until a portion of the disturbance finally separates from the bulk of the liquid and become a droplet**

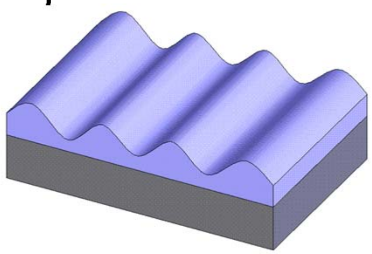


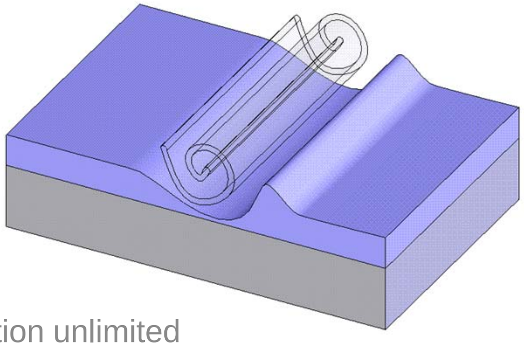
- **Could also provide estimates of initial droplet size and number if the initial disturbances were known**

What is a Disturbance Type?

- **There are various disturbance initiation mechanisms which each generate slightly different disturbances on the film**
- **Before the theory can be applied, disturbance types must be identified**
  - A review of film literature suggested four main disturbance types
    - Ligaments due to liquid turbulence
    - Waves due to hydrodynamic instabilities
    - Wave-like structure(s) caused by large-scale gas-phase structures
    - Ligaments due to gas-phase turbulence

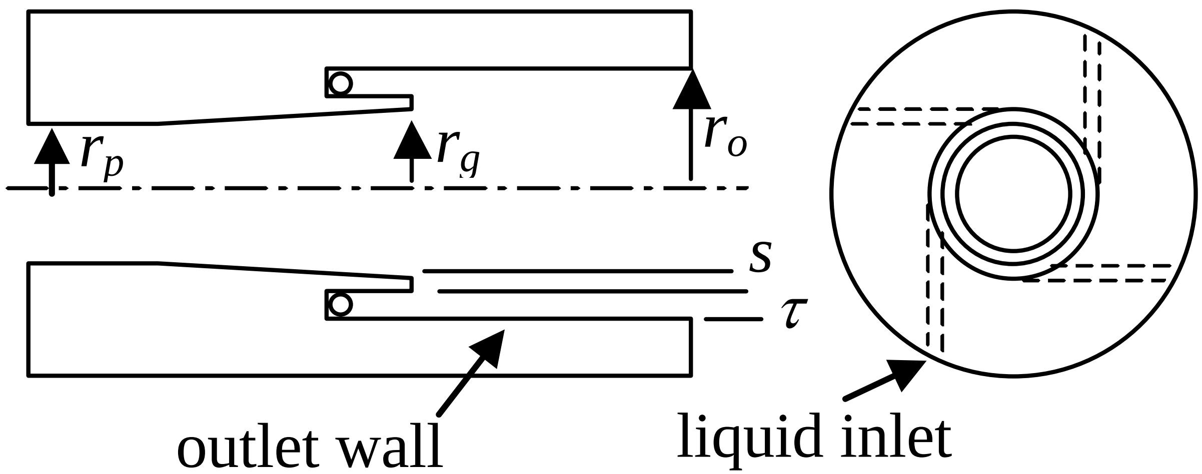






Gas-Centered Swirl Coaxial injector

- **Injector is of interest in oxygen-rich cycles using hydrocarbon fuels, and is similar to what is used on Russian-built kerosene engines**



- **Swirling liquid is introduced along the wall creating an annular sheet**
- **Sheet is sheared and atomized by a high-velocity annular gas flow (unswirled)**

Scaling

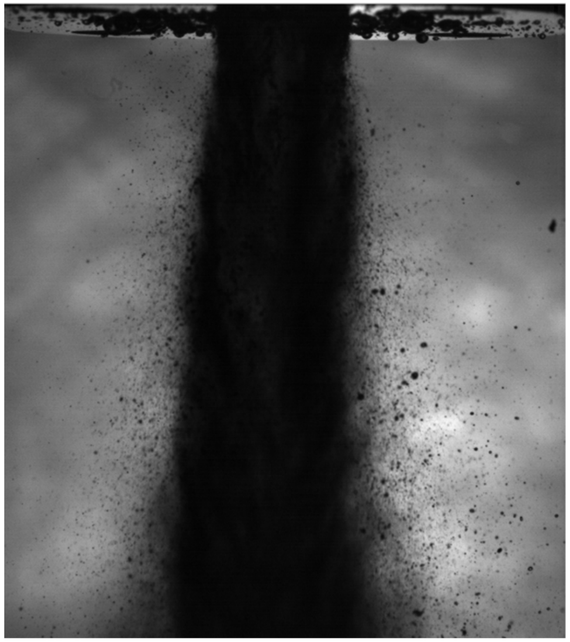
- **The generalized atomization description can provide scaling guidance to be used for lower-cost testing and as design criteria**
  - Specifically, testing at atmospheric conditions is desirable, since pressures needed to match density ratios seen in engines are 40-65 atm

$\frac{\rho_g v_g^2}{\rho_l v_l^2}$	Aerodynamic (shear)	$O(10^2)$-$O(10)$
$\frac{1}{Re_l}$	Viscous	$O(10^{-2})$-$O(10^{-3})$
$\frac{1}{We_l}$	Surface tension	$O(10^{-2})$-$O(10^{-4})$
$\left(\frac{v_{rot}}{v_l}\right)^2$	Centrifugal	$O(10^{-2})$-$O(10^{-3})$

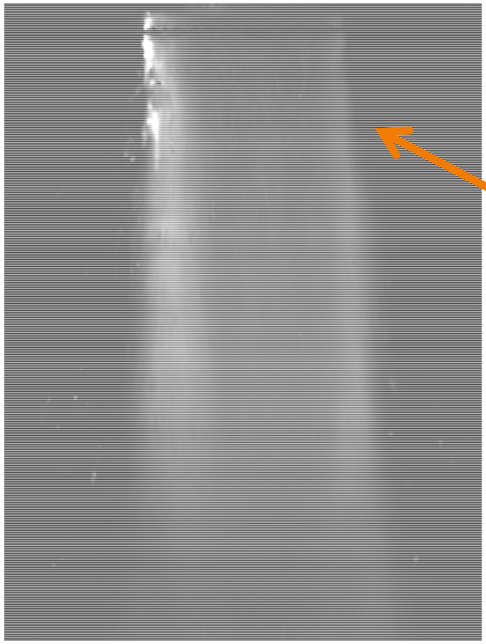
2+ orders of magnitude larger. Responsible for first-order effects

Verification of Scaling

- **For predicting combustion performance, droplet size, velocity and number density are important**
- **The optical density of the spray has prevented making these measurements**



Broadband Backlight



Laser Sidelight

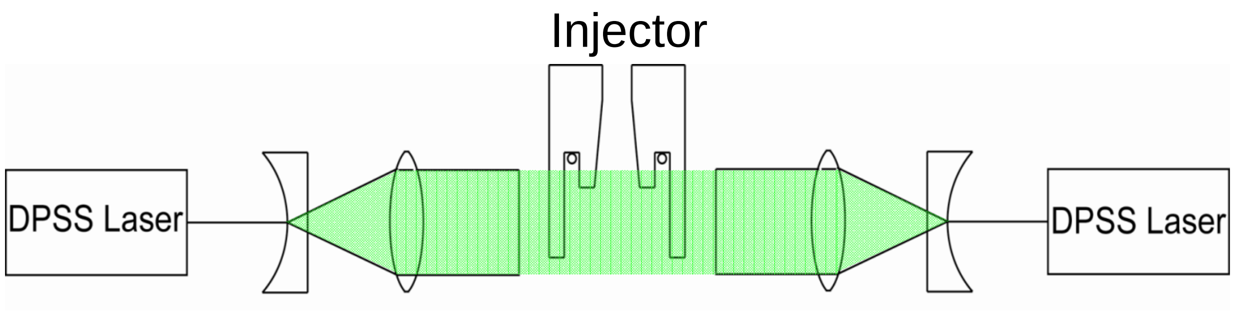
Scattering attenuates laser signal

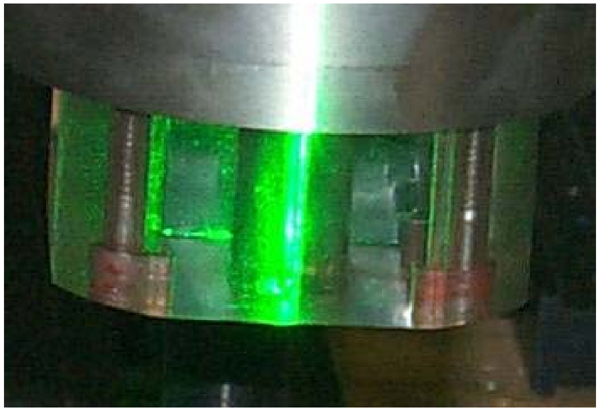
Intact Liquid

- **The majority of atomization for this injector occurs within the injector body where optical density is lower**
  - Measurements of the intact liquid length and the change in height along the injector's axis can be made
- **Atomization rate is often related to atomization performance, so we will use intact liquid length for verification**
  - This is not a unique approach, it's been used in rocket studies of shear coaxial injectors for decades ("dark core length")
  - But this is an annular liquid sheet, so access is difficult and correspondence with earlier work on shear coaxial jets is unlikely

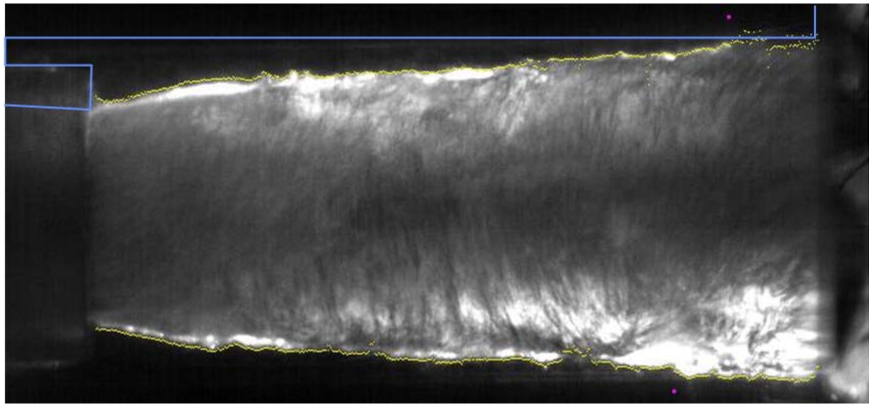
Experimental Set-Up

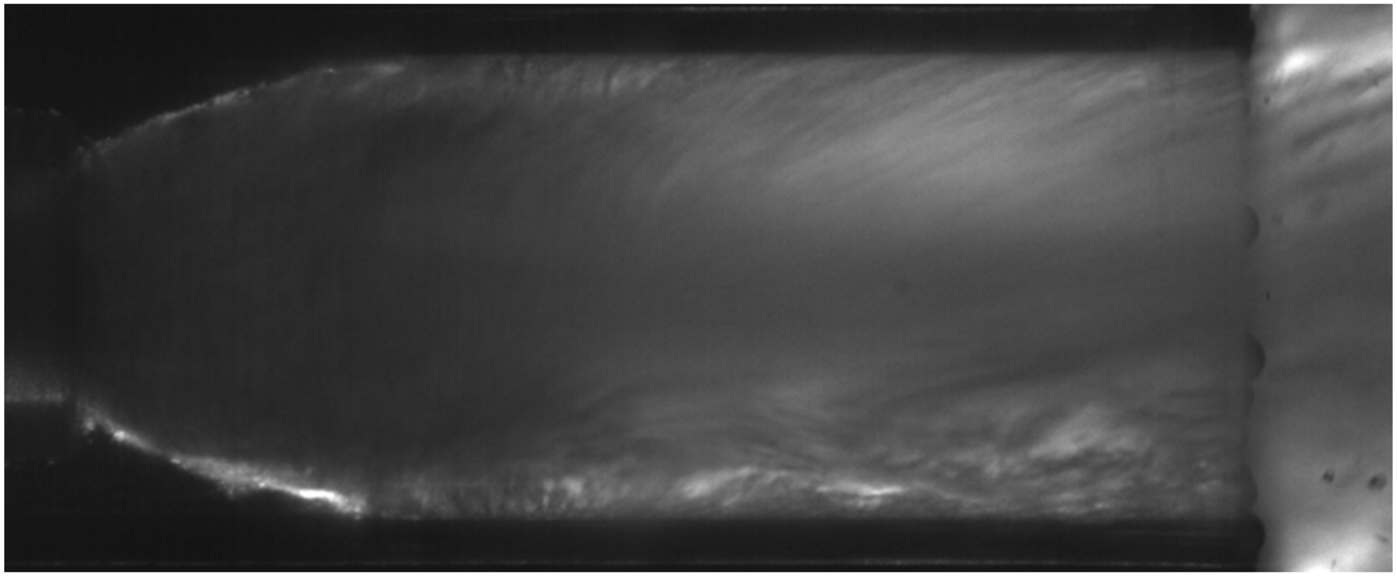
- **Dual-laser sheets just off of injector centerline, perpendicular to the camera**
  - Slight off-center of fractions of millimeters greatly improves forward scattering of light
- **Modular injector constructed to change (independently) swirl level, outlet diameter, initial thickness for liquid and height of shelter**





Inside the Injector

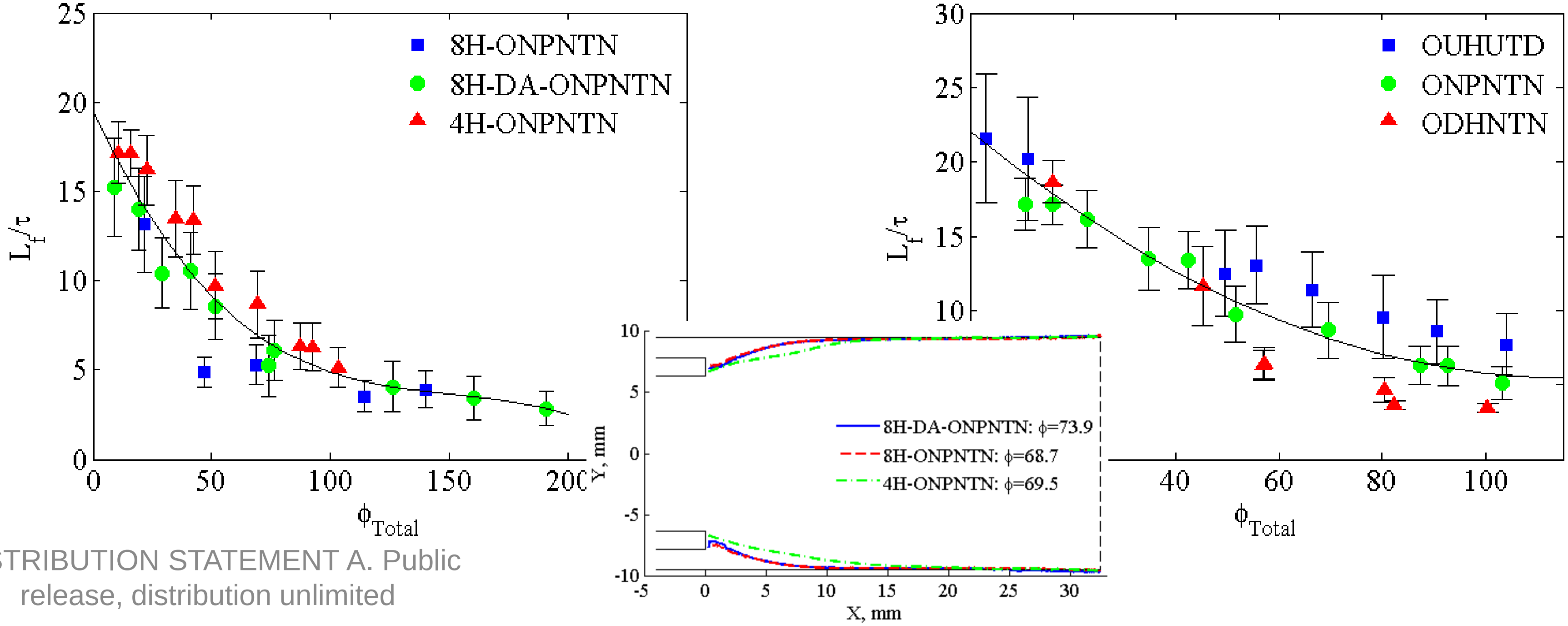




DISTRIBUTION STATEMENT A. Public release, distribution unlimited

Does Scaling Work?

- **How do we define a single velocity for the liquid and gas in this dynamic environment?**
  - Because we want to use this approach for low-cost experiments, definitions must be a priori
  - Basic velocity definitions based on set mass flow rates and inlet diameters were used



Swirl Effects

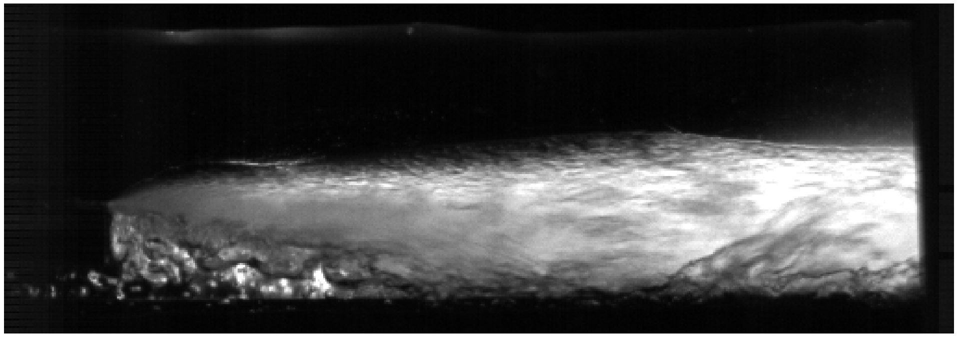
- **Agreement is good, and there is something very surprising, the vector of the liquid velocity is not important for scaling atomization rate**
  - If annular velocity of liquid is used then data collapses into families of curves based on swirl level—indicates that experiments vary swirl enough to capture any effect
  - Simplified velocity definition does not capture the acceleration of the liquid and gas which may play a role here
  - Swirl merits additional investigation

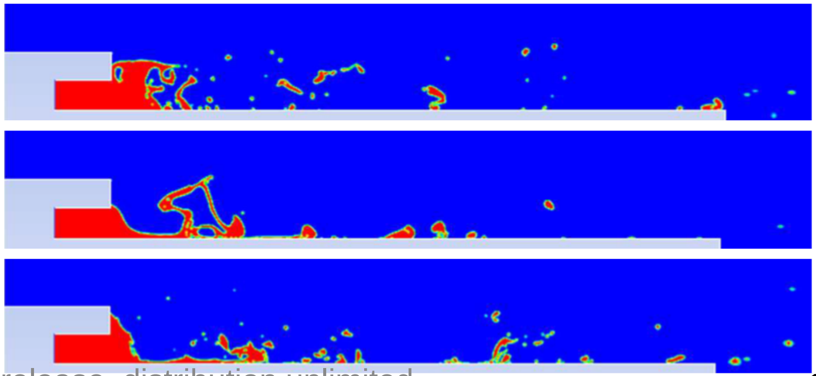
High Swirl

Low Swirl

What about Zero Swirl?

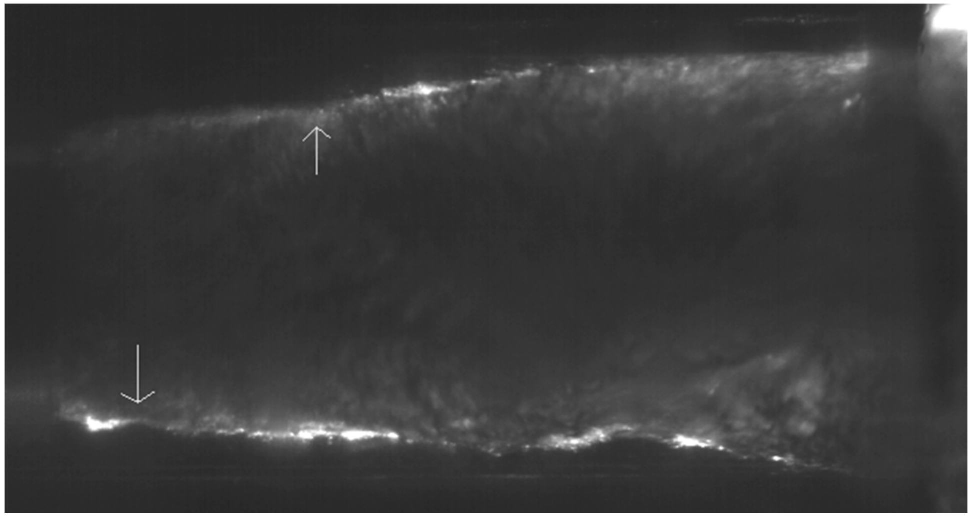
- **To further investigate, we considered the extreme case where there is no swirl**
- **As expected, lack of swirl creates a very dynamic film which, on average, atomizes more rapidly than the swirling film**
- **However, a good boundary condition (filling of the sheltered area) cannot be achieved and dynamics are severe enough to disrupt velocity and rms measurements in a flat geometry**



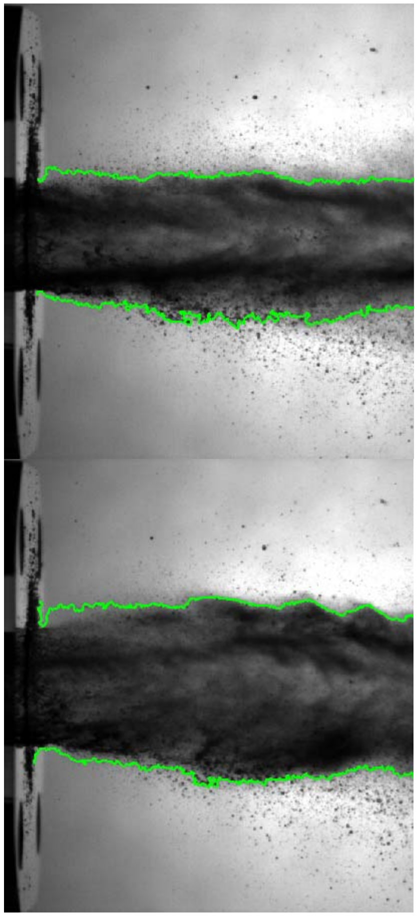


More Complexities

- **Additionally, some of the film boundaries clearly exhibited periodic instabilities**
  - Frequencies in atomization can couple with combustion and the rocket chamber and be catastrophic



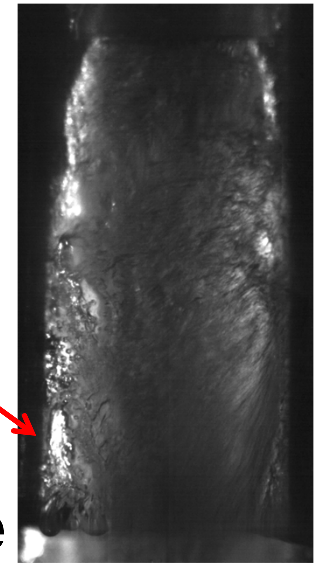
"Pulsing" behavior



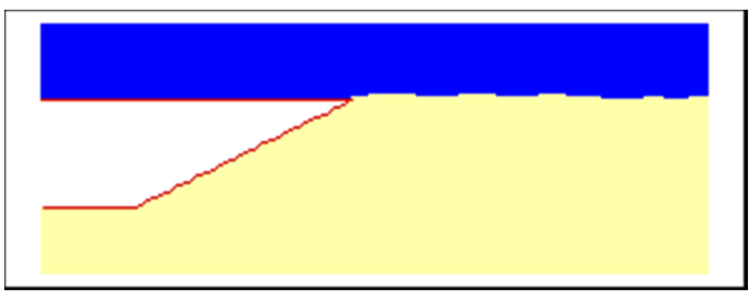
Comparison of Unsteadiness

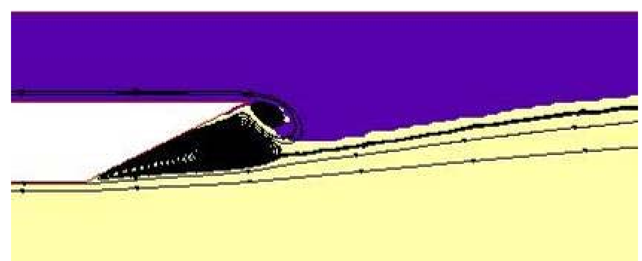
- **Flapping appears to be caused due to complex flow separation at the injector exit**
  - This is a fundamentally 3D, unsteady process that is complex and costly to model, so it has not yet been attempted

Entrained, no droplet flow

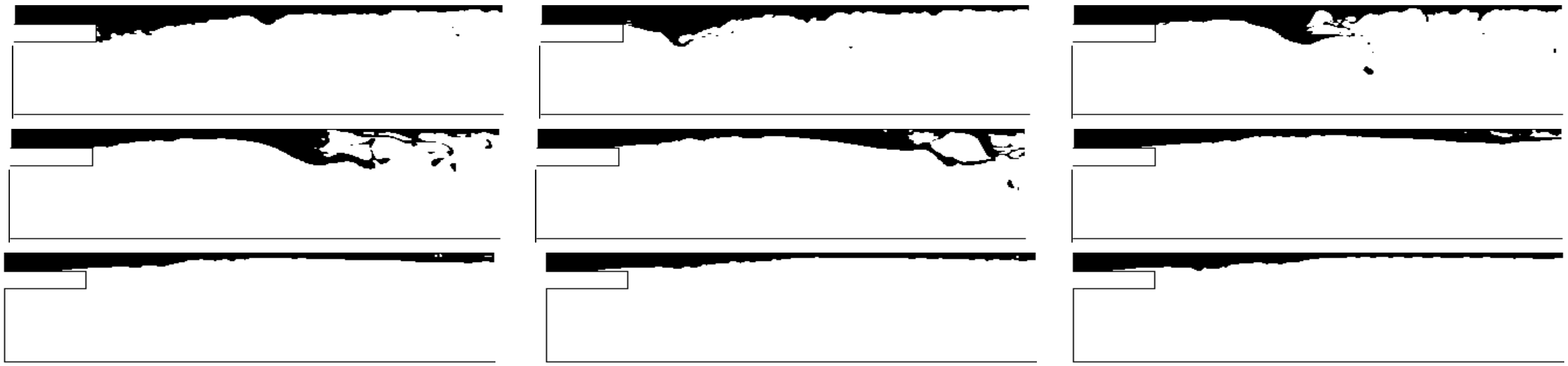


- **Pulsing is (nearly) axisymmetric, can a simple computational model help us understand this behavior?**
  - Axisymmetric with swirl using FLUENT and its VOF model for the boundary



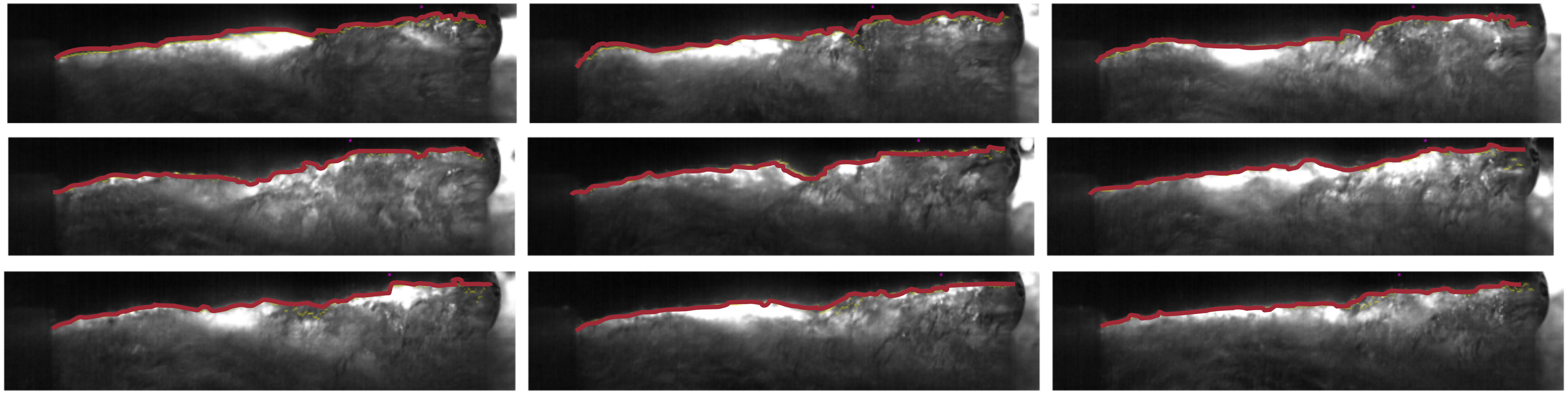


Comparison of Unsteadiness



Axisymmetric CFD (VOF in Fluent) results every 1.5 ms

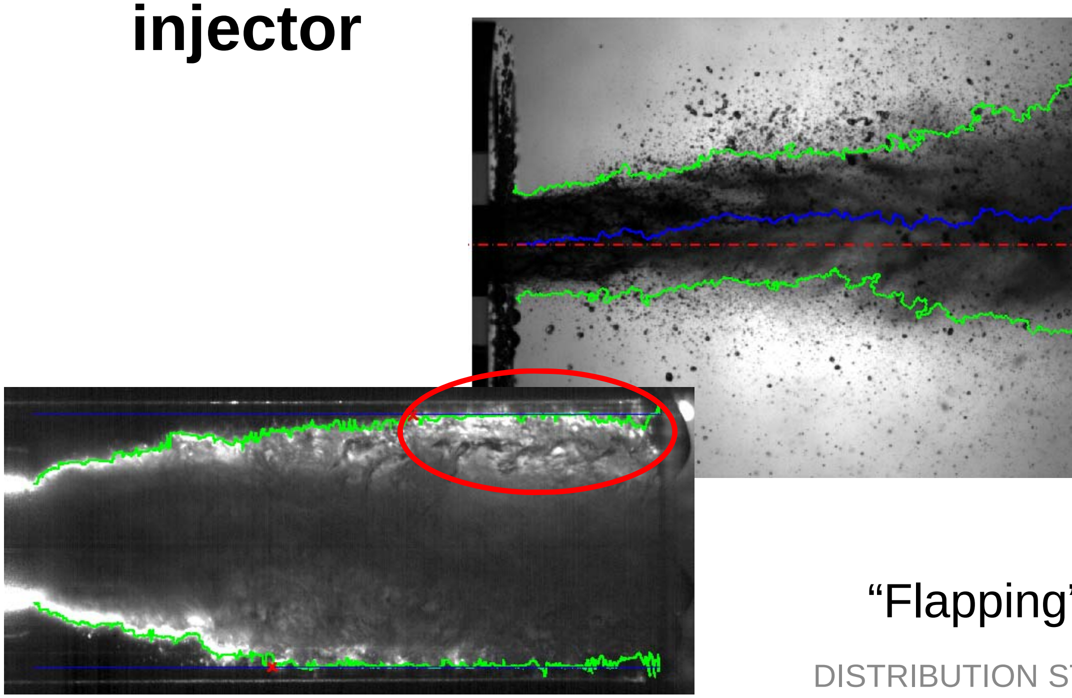
Experimental results every 0.5 ms, MFR ~10*above results

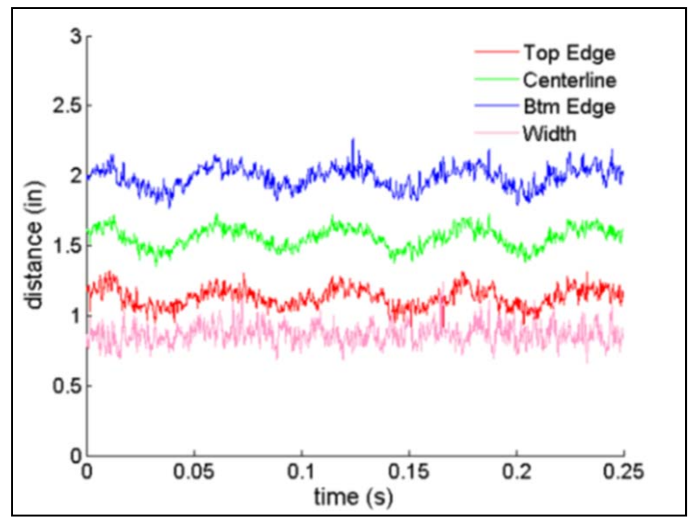


- **While qualitative agreement can be achieved between model and experiment, not at matching conditions**

More Complexities

- **Complex interactions involving swirl and the sudden expansion created other periodic behaviors**
  - This flapping could impact mixing between injectors or the heat transfer to the wall of the combustion chamber
- **Both periodic behaviors can be controlled through injector geometry—at the lip or at the outlet of the injector**

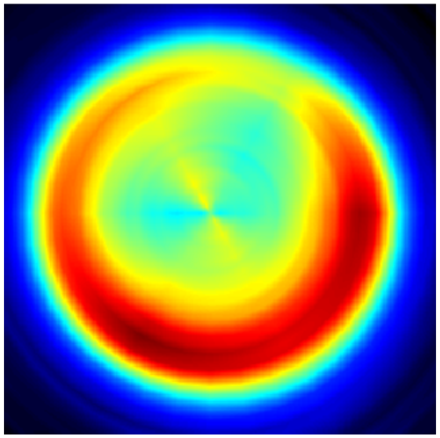




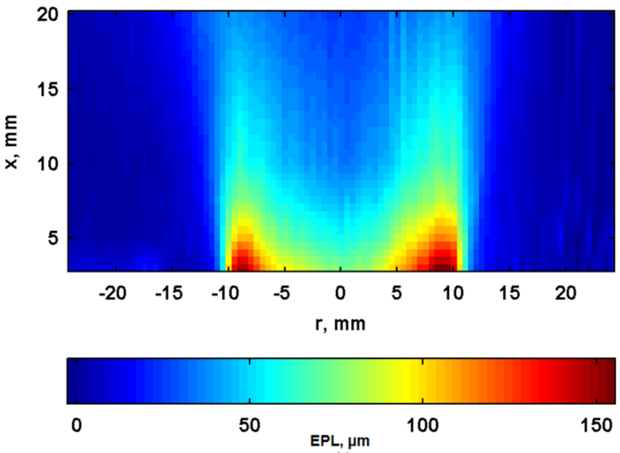
"Flapping" behavior

Other Diagnostics

- **Other, cutting-edge techniques have been developed by AFRL or through AFRL funding in an attempt to overcome the challenges of optically dense sprays**
- **Time-gated ballistic imaging provides a shadowgraph of large (intact) liquid structures at the injector outlet**
  - Gate only admits singly-scattered photons

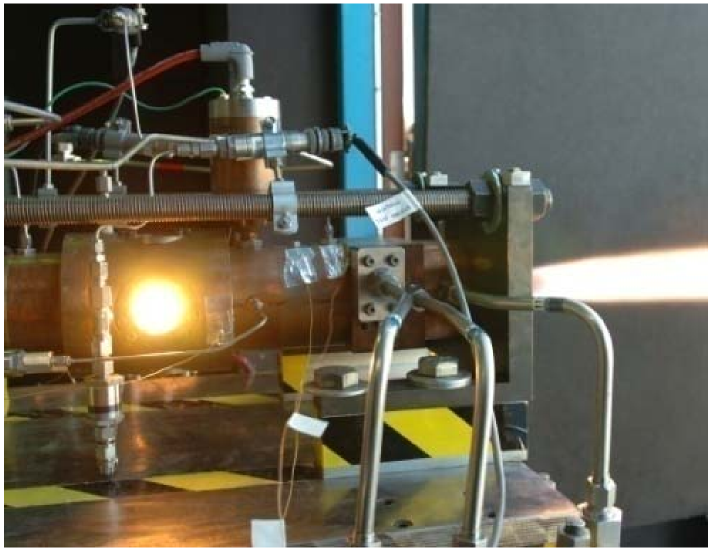


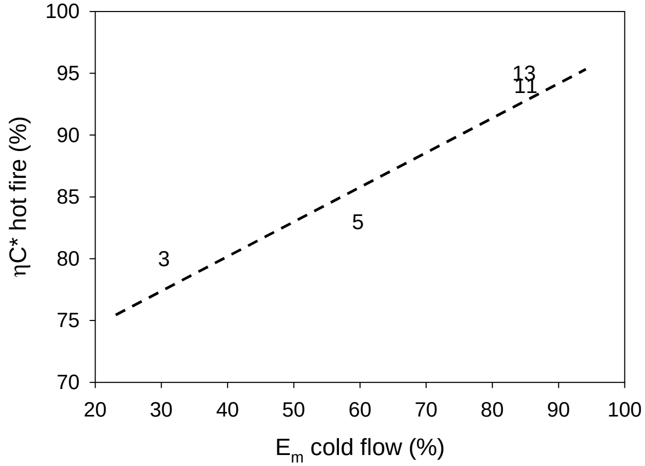
- **X-ray radiography provides mass distribution and mass-weighted acceleration information**
  - X-ray interaction with water is predominantly absorbing, not scattering
  - High-power source at Argonne National Laboratory makes quantitative measurements easily achievable



Combusting Flows

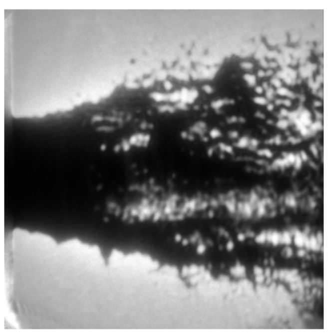
- **Combing data provides a set of design criteria**
  - Includes recommendations for testing needed to verify the design and for design refinement
- **Demonstrating that these cold-flow-derived guidelines are effective predictors of hot-fire performance is needed**
- **C* efficiency measurements from very similar injectors indicate basic approach is sound**



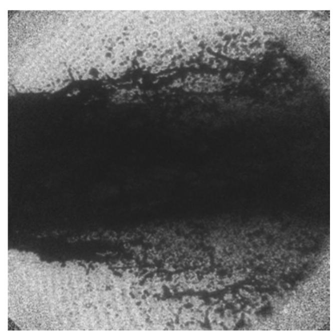


Hot-fire Results

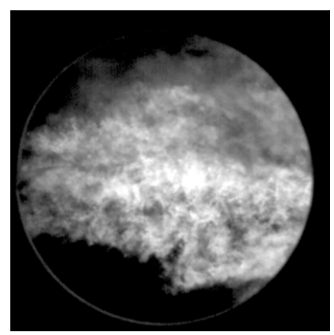
- **Window has thus-far provided only qualitative video images**
  – Optical density due to soot and line-broadening effects have prevented us from collecting temperature and/or species profiles from CARS, PLIF, chemiluminescence and similar techniques
  – We've helped developed high-speed laser techniques to overcome some of these issues
- **Highly instrumented engine will provided additional high-quality quantitative data in the future**



Cold-flow
Ballistic Imaging



Cold-flow
Shadowgraphy



High-speed
Flame Image

Future Outlook

- **The process of developing design criteria for an injector has been briefly reviewed from initial identification of basic physical models through scaling laws to greater complexity**
- **The developed guidance is useful for reducing engine development costs because a feasible design can be achieved more quickly and lower cost testing can be used for refinement**
- **Details of our recommended approach are already being utilized BUT there is much work that remains**
  - Demonstrate applicability in combustion environment
  - Integrate into CFD and show its predictive capability
  - Move beyond single injectors—injector interactions with other injectors and walls